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Turbulent Diffusion Behind Vehicles: Experimentally Determined Influence of Vortex Pair in Vehicle Wake

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16. ABSTRACT

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Vertical and lateral profiles of mean and fluctuating velocities and mean tracer concentration were obtained. Profiles were taken at distances of 15 - 60 model heights downstream. Two exhaust source positions were used: at the center of the rear of the vehicle and on the side just behind the rear wheel. It was found that the scale vehicles induce a pair of vortices in the wake that modify the velocity and concentration patterns in a minor way from that of the block car.

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TURBULENT DIFFUSION BEHIND VEHICLES: EXPERIMENTALLY DETERMINED INFLUENCE OF VORTEX PAIR IN VEHICLE WAKE

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(*First received* 31 *October* 1986 *and in final form* 6 *April* 1987)

Abstract—The wake of a moving vehicle was simulated using a wind tunnel with a moving floor. The vehicle models, both block-shaped and 'true' scale models of actual automobiles, were held in a fixed position while the floor moved at the upstream air speed. This simulates an automobile travelling on a straight highway in still ambient air.

Vertical and lateral profiles of mean and fluctuating velocities and mean tracer concentration were obtained. Profiles were taken at distances of 15–60 model heights downstream. Two exhaust source positions were used: at the center of the rear of the vehicle and on the side just behind the rear wheel. It was found that the models of true vehicles induce a pair of vortices in the wake that modify the velocity and concentration patterns in a minor way from that of the block-shaped vehicle.

Key word index: Air pollution, diffusion model, highway, motor vehicle, wakes, wind tunnel.

NOMENCLATURE

c	Concentration of tracer
H, W	height, width of the vehicle
Q	tracer flow rate
U_{ref}	freestream velocity (or vehicle speed)
$\bar{u}$, $\bar{w}$	mean air speed relative to vehicle in downstream and vertical directions, respectively
u	velocity deficit $= U_{ref} - \bar{u}$
v', w'	velocity fluctuation in lateral and vertical directions, respectively
x, y, z	coordinate system with origin at center of rear of vehicle at ground level
χ	non-dimensional concentration $(cU_{ref}H^2/Q)$.

1. INTRODUCTION

Since the automobile is a major contributor to air pollution, methods of predicting concentrations of automobile exhaust gases near roadways are needed for the planning and design of roads and nearby structures. In a previous effort (Eskridge and Thompson, 1982), extensive laboratory measurements were made to determine the aerodynamic wake characteristics of a block-shaped model of an automobile. A wind tunnel was constructed with a floor that moved with the freestream air speed. A scale-model vehicle mounted in the test section of this wind tunnel simulated a vehicle moving through a calm environment. That work was performed to evaluate a theoretical model (Eskridge and Hunt, 1979) and obtain empirical values of the model's parameters necessary to apply the theory to a numerical prediction model for computing automobile exhaust diffusion (Eskridge *et al.*, 1979). A block-shaped vehicle was used in the laboratory study to avoid the more complicated wake structure of a 'true' vehicle and obtain a more general result than would be obtained for a particular vehicle make. The results of the laboratory study led to some significant modifications of the original theory which were incorporated into the ROADWAY model for predicting velocity and turbulence fields and pollution concentrations near highways. The ROADWAY model is described by Eskridge and Catalano (1987), and evaluated with concentration measurements obtained in the laboratory for the block-shaped vehicle by Eskridge and Rao (1986).

The wake of a true vehicle contains a counter-rotating vortex pair which can be related to the lift generated by the streamlined shape of the vehicle. In this study, velocity, turbulence and tracer-gas concentration measurements have been made for scale models of actual vehicles. While these measurements demonstrate the presence of a counter-rotating vortex pair in the vehicle's wake, the effects on the concentration field are minor for tracer gases released along the centerline of the vehicle.

Chock (1977) suggests that plume rise should be considered as another aspect of near-highway diffusion of automobile exhaust. The buoyant plume rise resulting from the heated exhaust would be expected to be small if the exhausted gases are rapidly mixed in the turbulent wake.

The tailpipes on today's vehicles do not have a standard location. Most, however, terminate at the rear of the vehicle or on the side just behind the rear wheel.

*On assignment from the National Oceanic and Atmospheric Administration, U.S. Department of Commerce.

The exhaust from a tailpipe at the side of the vehicle could be influenced by the updrift region of the trailing vortex to, in effect, produce a plume rise. A series of experiments was performed to investigate the diffusion of exhaust from a side release and the influence of the vortex motion.

2. EXPERIMENTAL APPARATUS

Experiments were performed in the moving-floor wind tunnel described by Eskridge and Thompson (1982). Detailed descriptions of the wind tunnel, hot-film anemometry and data acquisition methods are presented in that article. Details of the tracer-gas release and concentration measurement systems are given in Eskridge and Rao (1986).

Model vehicles with scale ratios of 1/8 to 1/32 were tethered to remain in a fixed position on the moving floor of the test section (0.82 m wide by 0.71 m high) of a specially constructed wind tunnel. The air speed and moving floor speed of 1.9 m s^{-1} past the stationary vehicle simulated a vehicle moving along a flat highway under calm atmospheric conditions.

An X-configured, hot-film anemometer was used to measure mean velocity and turbulence components in the vehicle wake. By orienting the probe horizontally or vertically, the lateral or vertical component of velocity fluctuation v' or w', respectively, was determined. With the probe in the vertical orientation, the speed and angle of the flow can be used to compute the mean value of the vertical component of velocity, $\bar{w}$.

Concentration fields were generated by releasing a neutrally buoyant tracer gas (ethylene, 99.8% pure) from a diffuse source (porous stone ball, 1.4 cm diameter, at a height of $0.35H$) at the rear of the vehicle or from a brass tube (O.D. = 0.56 cm) behind the right rear wheel of one of the 1/12th scale vehicles at a height of $0.18H$. A flame ionization detector (Beckman, model 400) was used to determine time-averaged concentrations of the sample gas that was collected through a sampling port (0.16 cm diameter brass tube). A sampling time of 30 s (at a rate of 1 sample s^{-1}) provided repeatable results.

Model vehicles used were 1/8th, 1/12th and 1/32nd scale block-shaped vehicles, 1/12th and 1/32nd scale models of a Ford Mustang and a 1/32nd scale model of an AMC Javelin.

3. MEASUREMENTS

3.1. *Wake aerodynamics*

The presence and basic nature of the trailing vortex pair that exists in the wake of a streamlined vehicle are discussed by Scibor-Rylski (1975). This vortex pair has axes directed downstream from the vehicle and rotates inwardly on the top as shown in Fig. 1. This creates a downward flow in the central portion of the wake which will be quantified later. Effects of this vortex

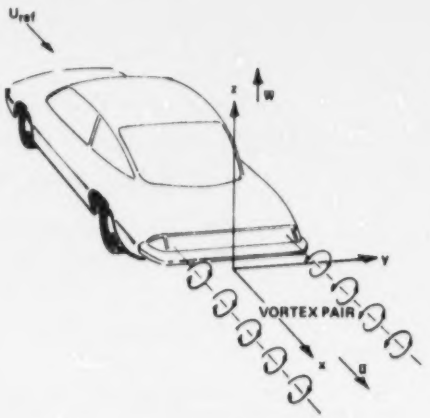


Fig. 1. Vortex pair in vehicle wake.

motion on the mean velocity in a vehicle wake can be observed in lateral profiles at various heights. The most dominant effect is the higher speed flow above the vehicle being drawn down into the center of the wake by the inward rotation. As an example, lateral profiles of mean velocity at a downwind distance of $30H$ and a height above ground of $0.5H$ are shown in Fig. 2 for a block-shaped vehicle and two true scale-model vehicles. Velocities in the wake are seen to be on the order of the freestream value U_{ref}, so it is more instructive to consider the velocity deficit $u = U_{ref} - \bar{u}$ (Fig. 3). The vertical component of the local turbulence intensity $\sqrt{\overline{w'^2}}/\bar{u}$ is shown for the three vehicles in Fig. 4. The turbulence intensity for the block-shaped vehicle is on the order of 25% higher than for the true vehicle models.

With an X-film probe in a vertical orientation, the mean speed and angle of the flow from horizontal are determined. Even within the near wake of the vehicle,

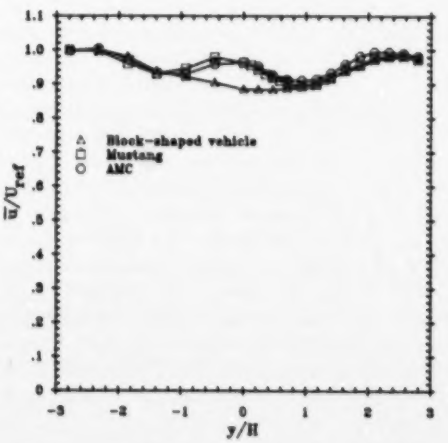


Fig. 2. Mean velocity in vehicle wake at $x = 30H$, $z = 0.5H$, for 1/32 scale models.

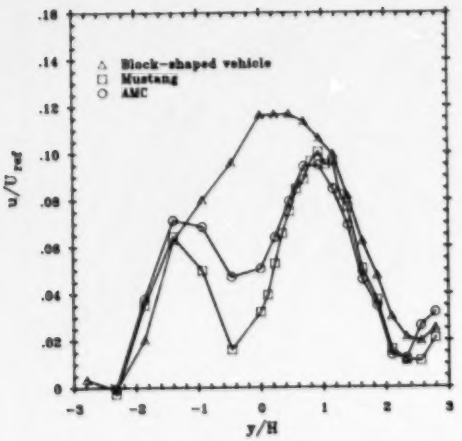


Fig. 3. Velocity deficit in vehicle wake at $x = 30H$, $z = 0.5H$, for 1/32 scale models.

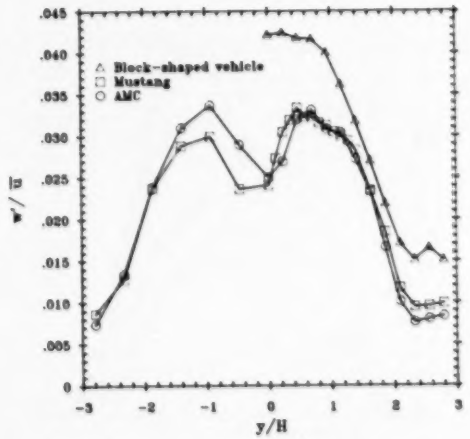


Fig. 4. Vertical component of turbulence intensity in vehicle wake at $x = 30H$, $z = 0.5H$, for 1/32 scale models.

the flow angles were small, on the order of 1°. Mechanical tolerances of the instrument carriage used to position the probe were also on this order. However, lateral profiles of velocity were taken with the probe in this configuration at a distance of $15H$ behind the 1/12th scale Mustang model. The data were used to compute the mean value of the vertical component at each measurement location. To correct for the errors introduced by the carriage, two vertical profiles were taken on the centerline of the wake: one with and one without the vehicle. Then, for each lateral profile, the flow angles were 'corrected' by subtracting from each the amount required to get the centerline measurement to match the corresponding value from the vertical profile with the vehicle minus the value for the empty tunnel.

An analysis of the influence of the induced vortex pair on the vertical velocity field was performed by comparing the wind tunnel velocity measurements with the computed velocity field for a pair of irrotational vortices. (An irrotational vortex has the tangential velocity component inversely proportional to the radius.) The presence of the surface was accounted for by locating an image pair of vortices below the surface; this avoided vertical flow at the surface but allowed a slip condition on the surface. This two-dimensional vortex calculation was applied to a transverse plane across the vehicle wake. The distortions of the vortex motions within the wake resulting from the vertical shear of the mean flow and turbulence in the wake are not included in the calculation. The two-dimensional irrotational vortex system is *not* suggested for the correct description of the vortex pair, but rather is used here as a simple method of demonstrating that the mean flow pattern in the vehicle wake is influenced by a vortex pair.

The spacing, height above the surface and strength of the vortices in the calculation were varied to obtain a general agreement with the measured values of the mean vertical velocity component. The geometry selected for the vortex pair used in the computation is shown in Fig. 5. Lateral profiles of the measured and computed vertical velocity component $\bar{w}$, defined as positive upward, are compared in Figs 6a and 6b. The agreement is much better at the higher levels than near the surface where the vertical shear in the mean velocity and turbulence levels are greater and tend to erode the contributions of the vortex pair.

Lateral profiles of the root mean square of the vertical component of velocity fluctuation as measured in the wake of the Mustang vehicle (Fig. 7) demonstrate that the velocity fluctuations are up to an order of five times the magnitude of the mean vertical velocity (Fig. 6).

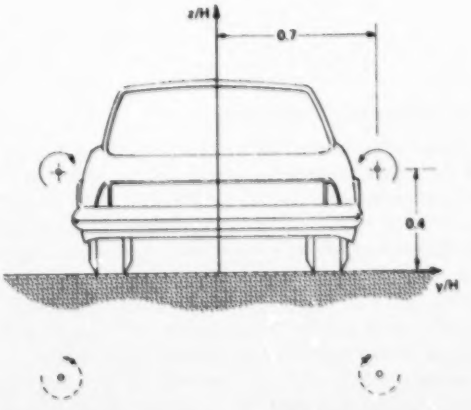
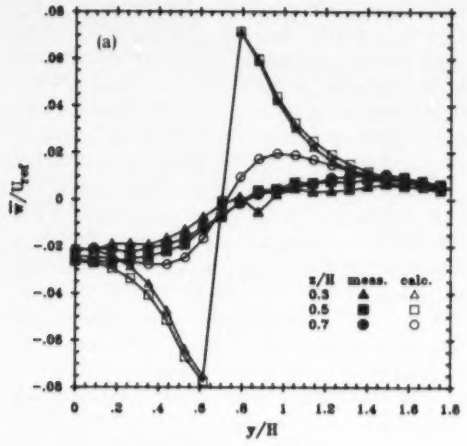


Fig. 5. Vortex positions for calculation of two-dimensional velocity field.



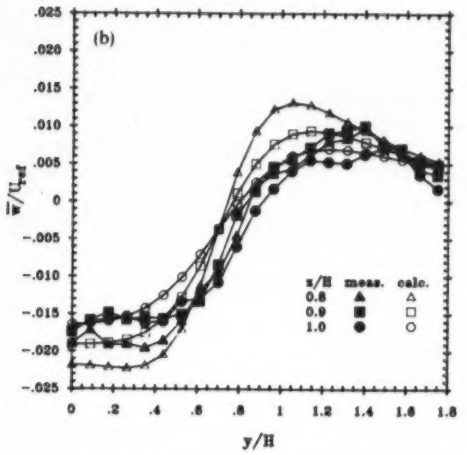


Fig. 6. Experimentally determined mean vertical velocity component as compared with vortex calculation at $x = 15H$, (a) $z = 0.3$ to $0.7H$, (b) $z = 0.8$ to $1.0H$ for 1/12 scale Mustang.

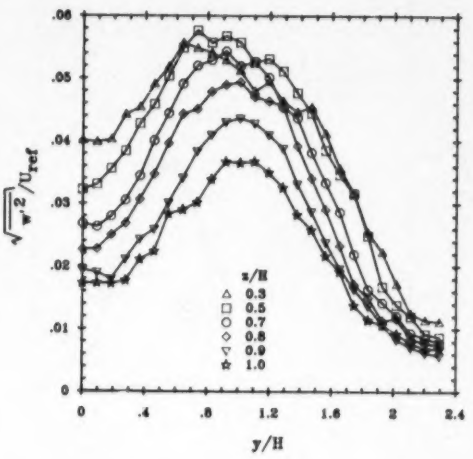
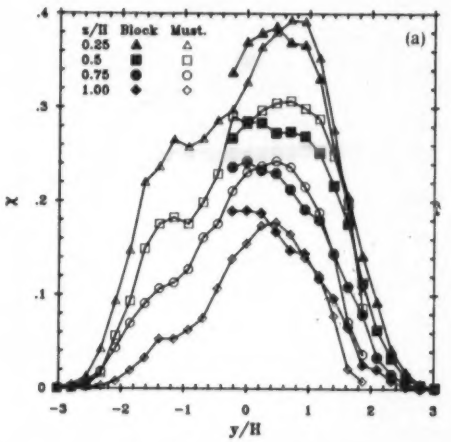


Fig. 7. Root mean square of the vertical component of velocity fluctuation at $x = 15H$ for 1/12 scale Mustang.



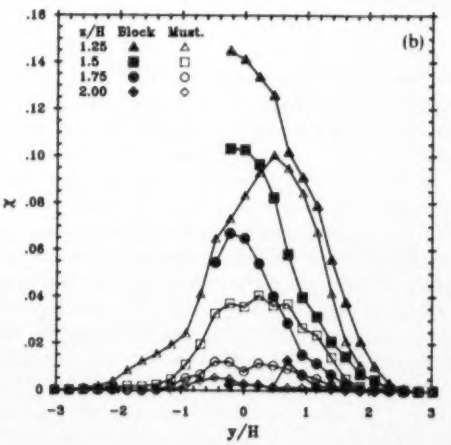


Fig. 8(a–b).

3.2. *Concentration measurements*

Exact simulation of the momentum and turbulence of the actual automobile exhaust was not possible. A diffuse source (a porous ball) located at the center of the rear of the vehicle was used to emit the neutrally buoyant tracer gas with negligible momentum. It was felt that the high turbulence level near the vehicle produces a well mixed region that rapidly spreads the exhaust gases and that releasing the tracer gas from a diffuse source would be an appropriate method.

Lateral profiles of the concentration of the tracer gas were obtained at distances of 30 and 60 H downwind of a 1/32 scale Mustang and are compared to those of the earlier study for a block vehicle (Figs 8a–d). The

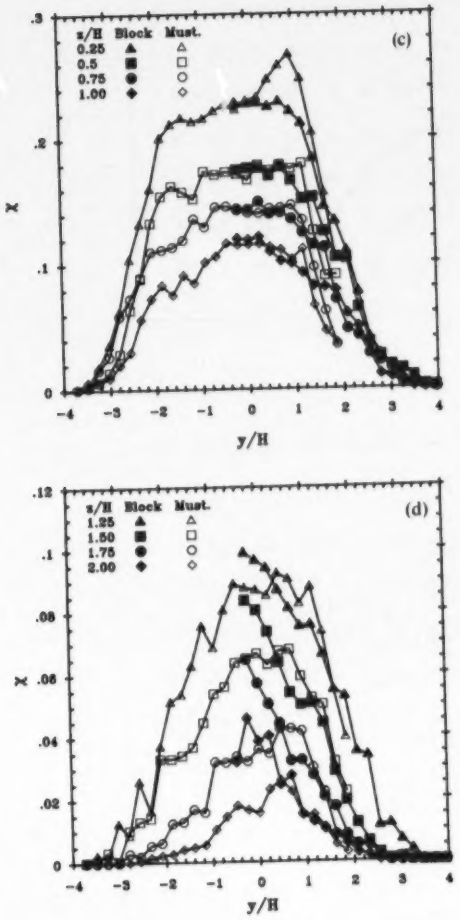


Fig. 8. Nondimensional concentration for block-shaped vehicle and Mustang (1/32 scale), center exhaust location at: (a) $x = 30H$, $z = 0.25$ to $1.0H$; (b) $x = 30H$, $z = 1.25$ to $2.0H$; (c) $x = 60H$, $z = 0.25$ to $1.0H$; (d) $x = 60H$, $z = 1.25$ to $2.0H$.

concentrations were normalized according to

$$\chi = cU_{ref}H^2/Q$$

where χ = the non-dimensional concentration
c = measured concentration
U_{ref} = freestream speed
H = vehicle height
and Q = emission rate of tracer gas.

At heights below H the concentrations for the block vehicle and the scale model vehicle are very similar. This is true at both distances $x = 30H$ and $60H$ (Figs 8a and c). For z greater than H, the concentrations for the block-shaped vehicle are somewhat higher than those for the true vehicle (Figs 8b and d). At these heights, however, the magnitude of the concentrations are below 25% of the maximum value at the given downwind distance.

Two factors could contribute to the differences at the higher levels. For the Mustang, the downward flow in the central portion of the wake induced by the vortex pair brings in fresh air to reduce the concentrations. The streamlined shape of the Mustang as compared to the block-shaped vehicle has a much lower drag coefficient (perhaps 0.3 or 0.4 as compared to 1.0). The strength of the wake, however, in terms of the magnitude of the velocity deficit and turbulence intensity, is only weakly related to the drag coefficient (proportional to the 1/4th power; see Eskridge and Thompson, 1982), so that the vortex mixing is the most probable cause of the differences.

Lateral profiles of tracer concentration were obtained for the side exhaust location for both model types. To better visualize the shapes of the plumes, contours of the normalized concentration field at $x = 30H$ are shown for both model types and both exhaust locations in Figs 9a–d. Figures 9a and 9b show the contours with the exhaust at the center of the rear of the vehicle are very similar for the two model types. The major difference is that the tracer has diffused to higher levels (see the 0.1 isoline) behind the block-

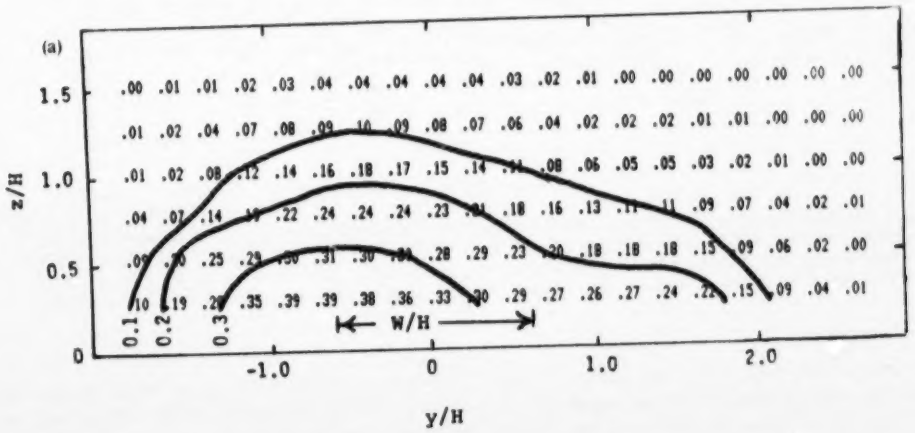


Fig. 9(a).

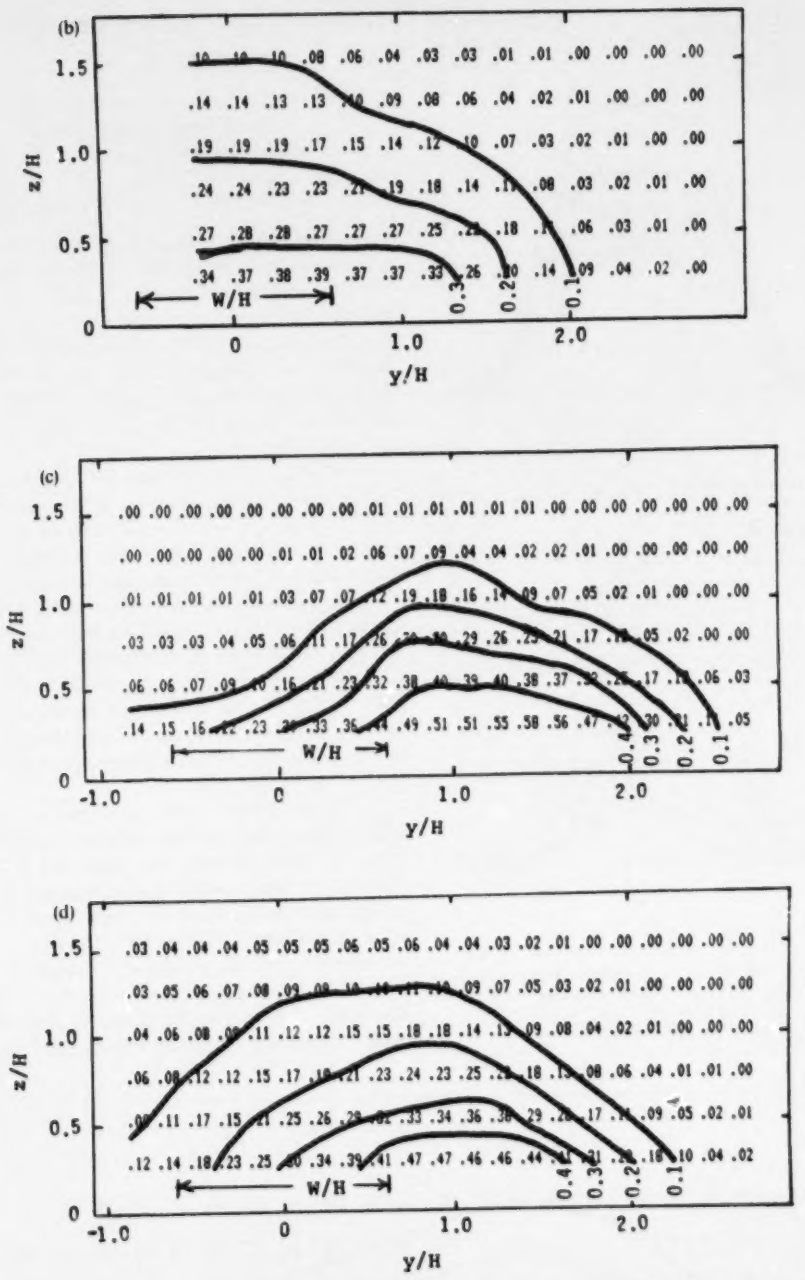


Fig. 9. (a) Nondimensional concentration for Mustang (1/32 scale) with center exhaust location, at $x = 30H$.
(b) Nondimensional concentration for block-shaped vehicle (1/32 scale) with center exhaust location, at $x = 30H$.
(c) Nondimensional concentration for Mustang (1/12 scale) with side exhaust location, at $x = 30H$.
(d) Nondimensional concentration for block-shaped vehicle (1/12 scale) with side exhaust location, at $x = 30H$.

shaped vehicle than behind the true vehicle. This is probably due to the trailing vortex pair behind the true vehicle which draws clean air down into the central region of its wake. The asymmetry of the concentration pattern for the Mustang (Fig. 9a) is due to the sensitivity of the alignment of the vehicle with the approach flow. Small changes in the angle to the flow resulted in noticeable lateral shifts of the concentration

field. Perfect alignment was not possible and the concentration pattern in Fig. 9a is typical for close alignment of the vehicle with the approach flow.

The results for the two model types with the side exhaust location are somewhat different. The pattern of the true vehicle (Fig. 9c) surprisingly shows a higher concentration near the ground than the block-shaped vehicle. It also shows the action of the trailing vortex in that air is advected downward near the center of the wake resulting in low centerline concentrations. The upward motion at lateral distances greater than $W/2$ advects the tracer and produces a more spiked plume cross-section than observed for the block-shaped vehicle (Fig. 9d).

In general, however, the differences between the concentrations for the side exhaust and center exhaust locations are small. At $x = 30H$, the maximum observed concentration for each of the four cases (block-shaped vehicle, center exhaust; block-shaped vehicle, side exhaust; scale car, center exhaust; scale car, side exhaust) was between 0.39 and 0.58. These values occurred at $z/H = 0.25$. At higher levels, however, the maximum observed concentrations for a given z/H for all vehicle and source location combinations have even less spread (for example at $z/H = 0.75$, the range is 0.18–0.19).

4. SUMMARY

The presence of a vortex pair in the wake of a scale model of a true vehicle has been demonstrated. The mean velocities induced by the vortex pair are small compared to the root mean square of the velocity fluctuations, $\bar{w} < \sqrt{\overline{w'^2}}$, within the turbulent wake. The influence on the mean flow was small except at heights greater than the height of the vehicle. Concentrations of a tracer released at the center of the rear of the vehicles were measured across transverse planes at downwind distances of $30H$ and $60H$. At heights below the vehicle height, the values for a block-shaped vehicle and a true vehicle model were essentially the same. For heights greater than the vehicle height, concentrations for the block-shaped vehicle were somewhat larger, however, at these heights the concentrations were less than 25% of the maximum observed at that distance.

When the tracer was released from the side exhaust location, a slight influence of the trailing vortex pair was seen in the concentration pattern behind the scale car. However, the magnitudes of the concentrations were very nearly the same as for the center exhaust location cases.

The ROADWAY model physics are based primarily on the block-shaped vehicle studies of velocity, turbulence and diffusion of tracer. The similarity of the concentration patterns in the wakes of the true vehicle and block-shaped vehicle models supports the application of the ROADWAY model to field situations.

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